Soft Gluon Resummation Effects in W^+W^- and Higgs Associated Production

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arXiv:1207.4207 [hep-ph], Sally Dawson, Tao Han, Wai Kin Lai, Adam Leibovich

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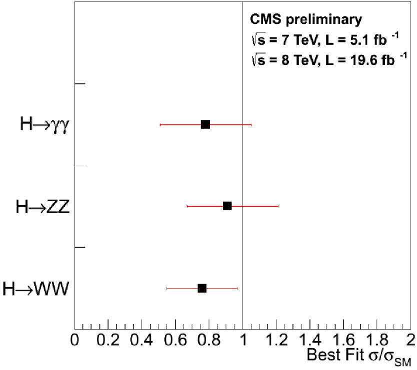
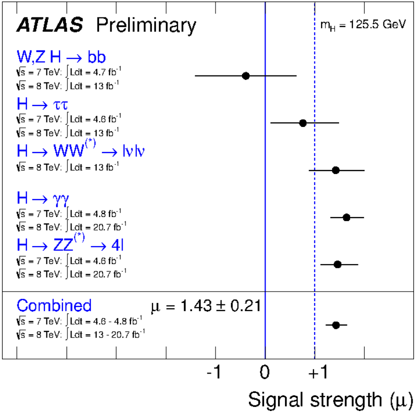
Outline

Discovery

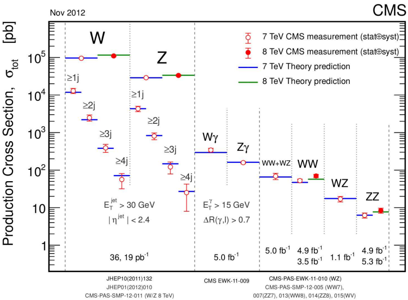


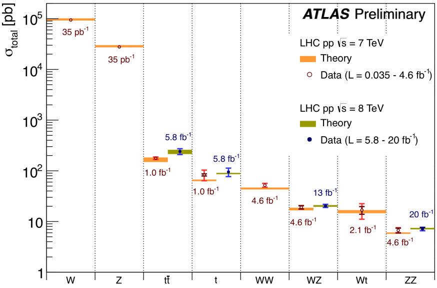


$$\mu_{\tau\tau} = 1.1 \pm 0.4$$
$$m_H = 125.8^{+0.4+0.4}_{-0.4-0.4}\ \mathrm{GeV}$$

$$\mu_{WW} = 1.01 \pm 0.31$$
$$m_H = 125.5^{+0.5}_{-0.6}\ \mathrm{GeV}$$

W^+W^- Anomaly?





- 7 TeV:
  $52.4 \pm 2.0\,(\text{stat.}) \pm 4.5\,(\text{syst.}) \pm 1.2\,(\text{lumi})$ pb
- 8 TeV:
  $69.9 \pm 2.8\,(\text{stat.}) \pm 5.6\,(\text{syst.}) \pm 3.1\,(\text{lumi})$ pb

- 7 TeV:
  $51.9 \pm 2.0\,(\text{stat.}) \pm 3.9\,(\text{syst.}) \pm 2.0\,(\text{lumi})$ pb

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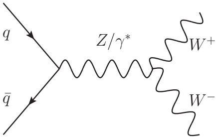
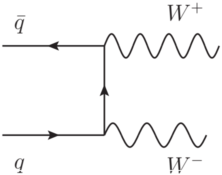
- SM from MCFM at NLO: 7 TeV: 47 ± 2 pb 8 TeV: $57.3^{+2.4}_{-1.6}$ pb
- W^+W^- consistently larger than SM prediction, even though ZZ and WZ very consistent.
- Recent interest in new physics processes that could explain excess.

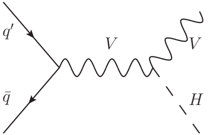
Curtin, Jaiswal, Meade, 1206.6888; Rolbiecki, Sakurai, 1303.5696; Feigl, Rzehak, Zeppenfeld, 1205.3468

Motivation

- Standard model $q\bar{q} \to W^+W^-$ is one of the major irreducible backgrounds to $H \to W^+W^-$, and this channel is not in complete agreement with SM predictions.
- Higgs main decay, $H \to b\bar{b}$, overwhelmed by QCD backgrounds. Most promising channel is Higgs production in association with a vector boson.
  - Leptonic decay of vector boson provides a hard lepton to trigger.
- For accurate measurements and to fully exploit the our chance to measure the properties of the Higgs at the LHC, need accurate predictions for signal and background.







Current Status

- $q\bar{q} \to W^+W^-$ known at NLO Ohnemus, PRD44, 1403 (1991); Frixione, NPB410, 280 (1993) Dixon, Kunszt, Signer, NPB531, 3 (1998)
- Rate for VH production known up to NNLO Brein, Djouadi, Harlander, PLB579, 149 (2004) Brein *et al*, EPJ C72, 1868 (2012)
- Infrared finite results occur due to cancellation of real and virtual soft divergences.
- However, at edges of phase space large logs associated with these divergences spoil perturbative convergence.
- Near partonic threshold ($z = M^2/\hat{s} \sim 1$): $\alpha_s^n \dfrac{\ln^{2n-1}(1-z)}{1-z}$
- At low transverse momentum ($p_T/M \ll 1$): $\alpha_s^n \ln^{2n-1}\left(\dfrac{M^2}{p_T^2}\right)$
- For accurate predictions of total rates and observables sensitive to these logs, they need to be resummed.
- Techniques for resumming both types of logs are well-known.

Threshold Resummation

- QCD factorization allows us to factorize the collinear and hard physics:
$$\frac{d\sigma}{dMd\cos\theta}=\int_\tau^1\frac{dz}{z}C(z,M,\cos\theta,\mu_f)\mathcal{L}\left(\frac{\tau}{z},\mu_f\right),$$
  - Hard scattering kernal C
  - Parton luminosity $\mathcal{L}$
  - $z=M^2/\hat{s}$, $\tau=M^2/s$.
- Near threshold, $z\to 1$, have large logs at every order in perturbation theory.
- Also have a new scale, the energy of soft gluon emissions $\sqrt{\hat{s}}(1-z)$.
- Have additional factorization between soft and hard scales near threshold:

$$C(z,M,\cos\theta,\mu_f)=H(M,\cos\theta,\mu_f)S(\sqrt{\hat{s}}(1-z),\cos\theta,\mu_f)+\mathcal{O}(1-z)$$

Threshold Resummation

- Near threshold:
$$\frac{d\sigma}{dMd\cos\theta} = \int_\tau^1 \frac{dz}{z} H(M,\cos\theta,\mu_f) S(\sqrt{\hat{s}}(1-z),\cos\theta,\mu_f) \mathcal{L}\left(\frac{\tau}{z},\mu_f\right),$$
- Separation of scales suggests and EFT approach: SCET
- The hard function is related to the Wilson coefficient of the appropriate SCET operator, i.e., the hard modes are “integrated out" of SCET.
- Each component evaluated at their relevant scales:
  - Hard function evaluated using full QCD at a hard scale μ_h
  - Soft function evaluated at a soft scale μ_s
- Demanding that the cross section be independent of μ_f, the RGE for the soft function can be solved for using the RGEs for the hard function and the DGLAP evolution for the pdfs.
- Then the large logs are resummed by evaluating each piece at their appropriate scale and RGE running to a common scale.
- Pointed out awhile ago that factorization leads to exponentiation of Sudakov logs Contopanagos, Laenen, Sterman, hep-ph/9604313

Hard Piece

- For W^+W^-, at one loop, have the amplitude squared.

$$\mathcal{M} = \mathcal{M}^{Born} - \frac{\alpha_s C_F}{4\pi}\left(\frac{4\pi\mu^2}{M_{WW}^2}\right)^{\varepsilon}\Gamma(1+\varepsilon)\left(\frac{4}{\varepsilon^2}+\frac{6}{\varepsilon}\right)\mathcal{M}^{Born} + \mathcal{M}^{v,reg}$$

- The UV divergences of SCET correspond to IR divergences of the full theory, hence by renormalizing SCET the IR divergences are canceled.
- Renormalization constant same as Drell-Yan:

$$Z = 1 - \frac{\alpha_s C_F}{2\pi}\left(\frac{1}{\varepsilon^2}+\frac{1}{\varepsilon}\ln\frac{\mu^2}{-M_{WW}^2}+\frac{3}{2\varepsilon}\right)$$

- After renormalizing the SCET operators:
$H(M_{WW}, \cos\theta, \mu) =$

$$\frac{\beta}{8\pi M_{WW}}\left\{\left[1-\frac{\alpha_s C_F}{2\pi}\left(\ln^2\frac{\mu^2}{M_{WW}^2}+3\ln\frac{\mu^2}{M_{WW}^2}+\frac{\pi^2}{6}\right)\right]\mathcal{M}^{Born}+\mathcal{M}^{v,reg}\right\}$$

Final Result

- Since renormalization of SCET operator the same as Drell-Yan, can use previous results to finish calculation Becher, Neubert, Xu, JHEP 0807, 030 (2008):

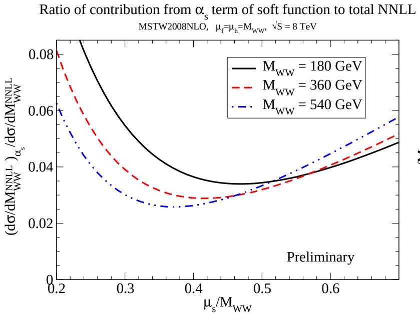
$$\begin{aligned}
\frac{d\sigma^{thresh}}{dMd\cos\theta} &= \int_\tau^1 \frac{dz}{z} C(z, M, \cos\theta, \mu_f)\mathcal{L}\left(\frac{\tau}{z}, \mu_f\right) \\
C(z, M_{WW}, \mu_f) &= H(M_{WW}, \mu_h) U(M_{WW}, \mu_h, \mu_s, \mu_f) \frac{z^{-\eta}}{(1-z)^{1-2\eta}} \\
&\times \tilde{s}\left(\ln\frac{M_{WW}^2(1-z)^2}{\mu_s^2 z} + \partial_\eta, \mu_s\right)\frac{e^{-2\gamma_E\eta}}{\Gamma(2\eta)}
\end{aligned}$$

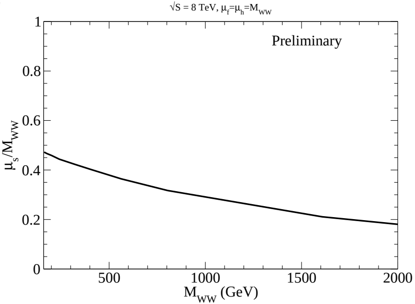
- U arises from RGE running and contains exponentiated logs:

$$\begin{aligned}
\ln U(M_{WW}, \mu_h, \mu_s, \mu_f) &= 4S(\mu_h, \mu_s) - 2a_{\gamma^V}(\mu_h, \mu_s) \\
&\quad + 4a_{\gamma^\phi}(\mu_s, \mu_f) - 2a_\Gamma(\mu_h, \mu_s)\ln\frac{M_{WW}^2}{\mu_h^2}
\end{aligned}$$

- $S(\nu, \mu)$ is a Sudokov exponent, $\eta = 2a_\Gamma(\mu_s, \mu_f)$
- Will present results at the NNLL order.

Soft Scale Choice

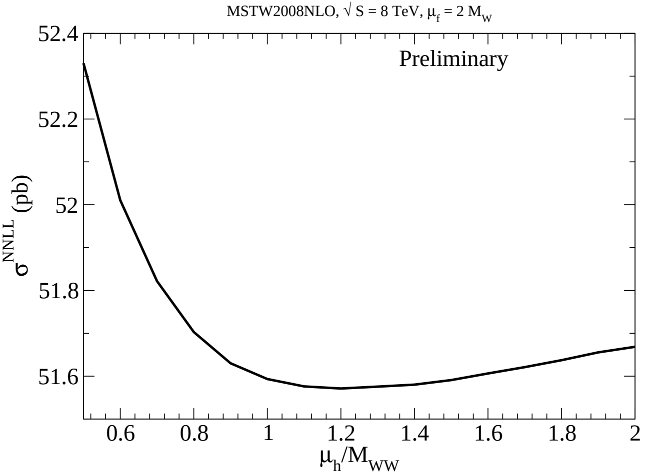




- $\tilde{s}$ is a perturbative function: $\tilde{s}(L,\mu) = 1 + \frac{C_F \alpha_s}{4\pi}\left(2L^2 + \frac{\pi^2}{3}\right)$
- The soft scale is chosen by minimizing the one-loop contribution, enforcing $\mu_s \propto (1-\tau)$ as $\tau \to 1$:

$$\frac{\mu_s}{M_{WW}} = \frac{1-\tau}{(1.542 + 6.270\sqrt{\tau})^{1.468}}$$

Hard Scale Dependence



Choose hard scale $\mu_h \sim M_{WW}$

Matching & Preliminary Results

- Now have all the pieces to get a final result.
- The threshold resummed piece is valid in the $z \to 1$ regime.
- The perturbative cross section is valid in the hard regime away from $z = 1$.
- Need to combine these two results to obtain result valid for all z:

$$d\sigma^{matched} = d\sigma^{Thresh.} + d\sigma^{F.O.} - d\sigma^{Leading}$$

- Leading singularity:

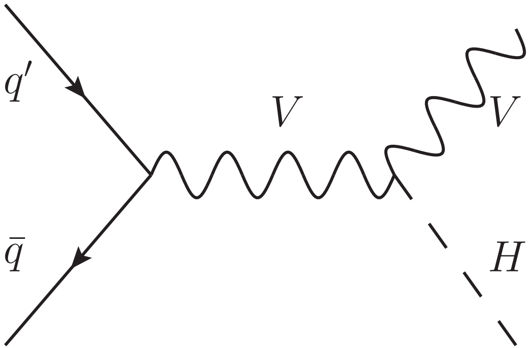
$$d\sigma^{Leading} = d\sigma^{Thresh}\big|_{\mu_s=\mu_h=\mu_f}$$

- Eliminates running between scales, leaving hard function and “+" functions in $(1-z)$ originating from the soft function.
- The leading singularity is subtracted to prevent double counting between the fixed order and resummed results.

Matching & Preliminary Results

- Using NNLL threshold resummation matched on NLO cross section, the preliminary results indicate the W^+W^- cross section is altered by $\sim 1-2$ pb relative to the NLO cross section with an uncertainty $\sim 1-2$ pb. Perturbative calculation appears well under control.
- Reminder:
  - $\sigma^{NLO} = 57.3^{+2.4}_{-1.6}$ pb
  - CMS measures $69.9 \pm 2.8\ (\mathrm{stat.}) \pm 5.6\ (\mathrm{syst.}) \pm 3.1\ (\mathrm{lumi})$ pb

Higgs Associated Production



Again, exactly the same as Drell-Yan. Hence, just reapply the results.

Scale Choice

- Choose soft scale to minimize effects of higher order corrections
  - $\mu_s^I = \frac{M_{VH}(1-\tau)}{2\sqrt{1+100\tau}}$ chosen to minimize 1-loop correction to soft piece
  - $\mu_s^{II} = \frac{M_{VH}(1-\tau)}{0.9+12\tau}$ chosen when 1-loop correction drops below 10%

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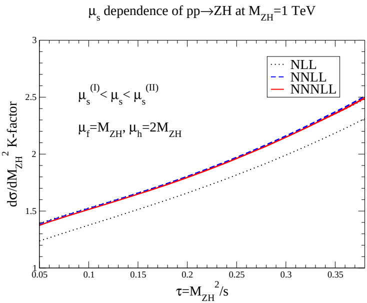
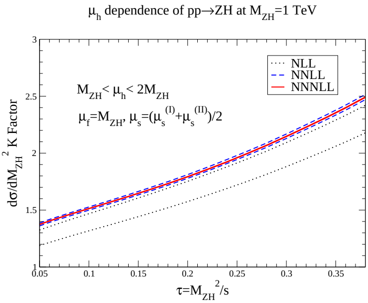
- Analyze scale variation via K-factor:

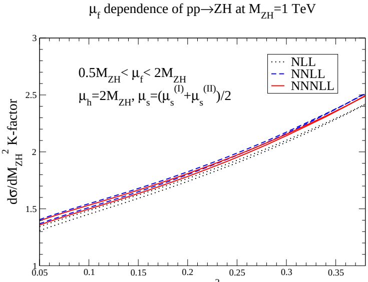
$$\frac{d\sigma}{dM_{VH}^2} \equiv K \frac{d\sigma}{dM_{VH}^2}\Big|_{\mathrm{LO}}$$

  - $d\sigma/dM_{VH}^2$ is a higher order QCD distribution

Scale dependence

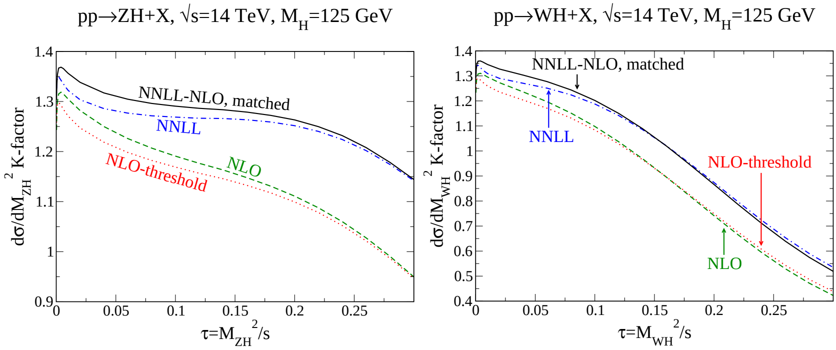






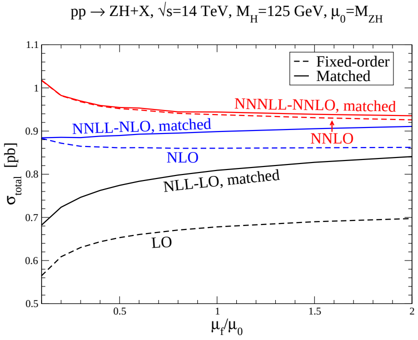
- $d\sigma/dM_{VH}^2$ chosen to be threshold resummed cross section.
- All cross sections evaluated using MSTW2008 NNLO pdfs

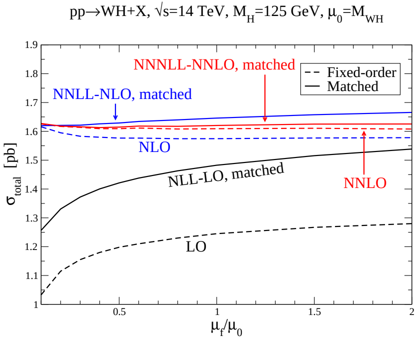
Invariant Mass Distribution



- K-factor evaluated with LO pdfs for LO distibution and NLO pdfs for all others.

14 TeV Cross Sections





- NNNLL has little effect.
- NNLL increases cross section $\sim 7\%$ for ZH and $\sim 3\%$ for WH
- Including threshold logs does not introduce added uncertainty.

- $\mu_s = \frac{1}{2}(\mu_s^I + \mu_s^{II})$
- $\mu_h = 2M_{VH}$
- MSTW2008 68% CL
- Use VH@NNLO for fixed order NNLO result

Brein, Djouadi, Harlander, PLB579, 149 (2004)

Transverse Momentum Resummation

- Apply impact parameter resummation to partonic cross section:

  CSS, Nucl.Phys. B250, 199 (1985); Bozzi *et al*, Nucl.Phys. B737, 73 (2006)

$$\frac{d\hat{\sigma}_{VH}}{dM_{VH}^2 dp_{T,VH}^2} = \frac{d\hat{\sigma}_{VH}^{resum}}{dM_{VH}^2 dp_{T,VH}^2} + \frac{d\hat{\sigma}_{VH}^{finite}}{dM_{VH}^2 dp_{T,VH}^2}$$

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- Resummed piece:

$$M^2_{VH}\frac{d\hat{\sigma}^{resum}_{VH}}{dM^2_{VH}dp^2_{T,VH}} = \frac{M^2_{VH}}{\hat{s}}\int_0^\infty db\frac{b}{2}J_0(bp_{T,VH})W^{VH}(b,M_{VH},\hat{s},\mu_r,\mu_f)$$

- $$W^{VH}_N(b,M_{VH},\mu_r,\mu_f) = H^{VH}_N\left(M_{VH},\alpha_s(\mu_r),\frac{M_{VH}}{\mu_r},\frac{M_{VH}}{\mu_f},\frac{M_{VH}}{Q}\right) \times\exp\left\{G_N\left(\alpha_s(\mu_r),L,\frac{M_{VH}}{\mu_r},\frac{M_{VH}}{Q}\right)\right\}$$
  - Factorizes into hard, H_N, and soft, G_N, pieces
  - $L = \ln(Q^2b^2/b_0^2)$
  - Q is so-called resummation scale.

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- $$W^{VH}_N(b, M_{VH}, \mu_r, \mu_f) = H^{VH}_N\left(M_{VH}, \alpha_s(\mu_r), \frac{M_{VH}}{\mu_r}, \frac{M_{VH}}{\mu_f}, \frac{M_{VH}}{Q}\right) \times \exp\left\{G_N\left(\alpha_s(\mu_r), L, \frac{M_{VH}}{\mu_r}, \frac{M_{VH}}{Q}\right)\right\}$$
  - $H^{VH}_N = \sigma_0(\alpha_s, M_{VH})\left\{1 + \frac{\alpha_s}{\pi}H^{VH(1)}_N + \left(\frac{\alpha_s}{\pi}\right)^2 H^{VH(2)}_N + \cdots\right\}$
  - $G_N = Lg^1_N(\alpha_s L) + g^2_N(\alpha_s L) + \left(\frac{\alpha_s}{\pi}\right) g^3_N(\alpha_s L) + \cdots$

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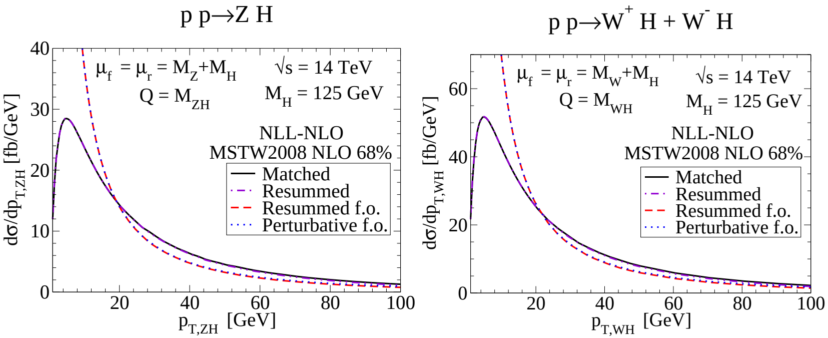
- Finite piece calculated at fixed order:

$$\left[\frac{d\hat{\sigma}_{VH}^{finite}}{dM_{VH}^2 dp_{T,VH}^2}\right]_{f.o} = \left[\frac{d\hat{\sigma}_{VH}}{dM_{VH}^2 dp_{T,VH}^2}\right]_{f.o} - \left[\frac{d\hat{\sigma}_{VH}^{resum}}{dM_{VH}^2 dp_{T,VH}^2}\right]_{f.o}$$

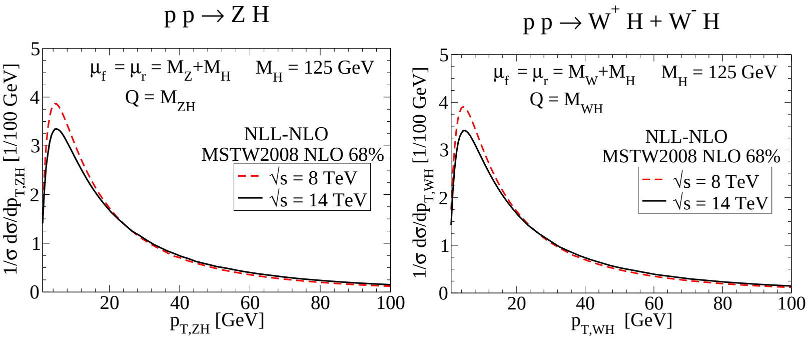
- High and low scale p_T successfully matched

Transverse Momentum Distribution



- As expected, perturbative expansions blows up at $p_T \to 0$

Normalized Transverse Momentum Distribution



Jet Cuts

- Jet vetoes can be important for eliminating background.
- Vetoing jets with a minimum p_T may be approximated by placing an upper limit on $p_{T,VH}$
- As shown, the perturbative calculation breaks down in this regime and the soft-gluon resummation is needed.
- There has been much recent work on the systematic resummation of the large logs associated with jet vetoes. Berger *et al*, JHEP 1104, 092 (2011)
  Banfi, Salam, Zanderighi, JHEP 1206, 159 (2012)
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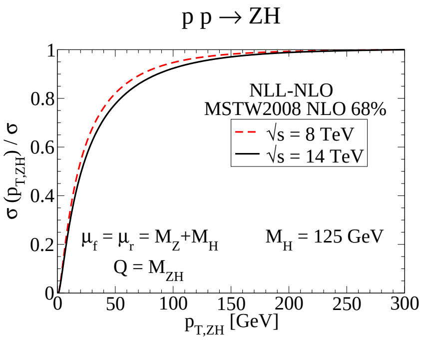
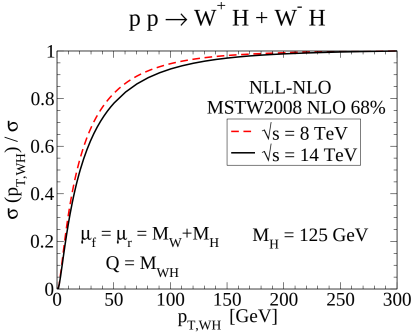
- To measure the approximate effect of the jet vetos define:

$$\sigma(p_{T,VH}) = \int_0^{p_{T,VH}} dq_{T,VH} \frac{d\sigma}{dq_{T,VH}}$$

Transverse Momentum Cut





$1-\frac{\sigma(p_{T,VH})}{\sigma}$	8 TeV	14 TeV
$p_{T,VH} < 20$ GeV	$\sim 45\%$	$\sim 50\%$
$p_{T,VH} < 30$ GeV	$\sim 33\%$	$\sim 37\%$

Conclusions

- We performed the threshold resummation for SM W^+W^- production and Higgs associated production.
- Preliminary results indicate that threshold resummation does not have much effect on the W^+W^- cross section, indicating that the perturbative calculation is well under control.
- Performed a detailed numerical analysis of VH production at the LHC.
- NNLL threshold resummed result increases fixed-order NLO cross section by $\sim 7\%$ for ZH and $\sim 3\%$ for WH
- NNNLL threshold resummation has little effect on the NNLO rate, demonstrating excellent convergence of the perturbative series.

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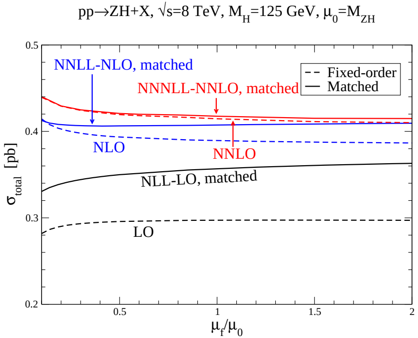
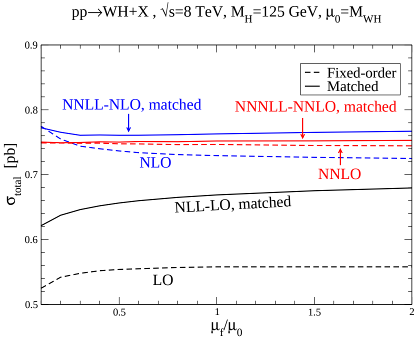
- NNNLL threshold resummation has little effect on the NNLO rate, demonstrating excellent convergence of the perturbative series.
- Performed the transverse momentum resummation of the VH system.
- Spectrum slightly harder at 14 TeV than at 8 TeV.
- Calculated the effects on the NLO cross sections of placing a cut on the p_T of the VH system. Expect such a cut to approximate a jet veto.
- Found p_T cut decreased NLO cross section by $33\% - 50\%$

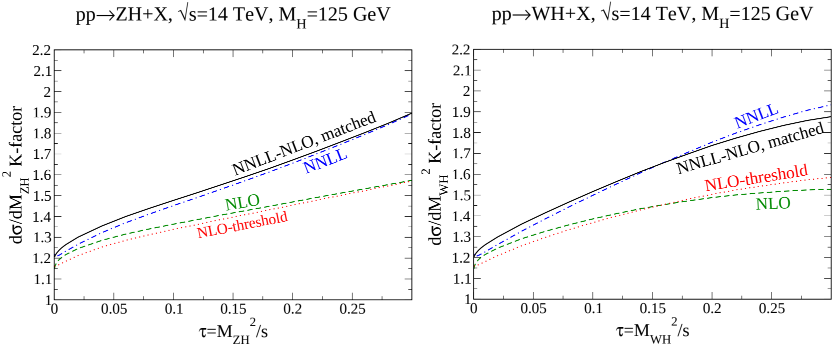
EXTRA SLIDES

8 TeV Cross Sections





Invariant Mass Distribution



- K-factor evaluated using NLO pdfs for all distributions.